

SPRAY CHARACTERIZATION OF THERMAL FOGGING EQUIPMENT TYPICALLY USED IN VECTOR CONTROL¹

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ABSTRACT. Droplet size spectra from different sprayers used to generate insecticide-laden fogs for controlling flying insects were measured by a laser diffraction instrument and Teflon-coated slides. The objectives of this work were to present not only information on spray-system droplet size generated by different sprayers, but to compare methodologies by which other similar systems can be evaluated and give applicators sprayer-system performance data. Data from 45 replicated spray tests, comprising 11 sprayers and 5 pesticides, showed a wide range in the droplet size spectra produced. The volume median diameter measurements ranged from 2.6 to 75.5 μm for diesel-diluted sprays and from 27.9 to 59.9 μm for water-diluted sprays. Similarly, the percent volume <20 μm ranged between 12.0–100% and 8.5–30.7%, for diesel- and water-diluted sprays, respectively. The droplet sizes measured by the swinging slide and laser diffraction methods were not consistent. The information presented aids users in sprayer selection and operation to produce the specific droplet size spectra required for a particular application.

KEY WORDS Atomization, droplet size, sprayer, thermal fogger, vector control

INTRODUCTION

One of the most common methods for controlling arthropod vectors, particularly mosquitoes, is the application of insecticides by either ground or aerial sprayers. When selecting application equipment and insecticides, applicators depend on recommended equipment operating parameters, as supplied by the manufacturer, along with recommended application rates and droplet sizes as detailed by chemical labels to ensure the most efficacious application. For vector control, the droplet size should be in the range 8- to 20- μm volume median diameter ($D_{V0.5}$) (Ledson and Matthews 1992, WHO 2006). As droplet size is one of the most significant factors affecting the success of vector control applications, it is critical to know baseline droplet and spray cloud characteristics for the equipment used.

Fogging machines generally fall into 1 of 2 types: thermal foggers and cold foggers. Thermal foggers are generally smaller, lighter, more portable, and less expensive (Mabbett 2006) than truck-mounted ultra-low volume (ULV) sprayers. Median droplet sizes of thermal foggers are generally

15 μm or less, the exact size dependent on several factors, including the particular nature of the solvent used in the mixture (Mabbett 2003, 2004). Smaller droplets result in denser fogs that remain suspended in the atmosphere for long periods of time (Himel 1971). Thermal fogging equipment varies with regard to equipment type and droplet sizes generated (WHO 1990, 2003, 2006). Matthews (1979) provided a detailed description of the various types of fogging equipment.

Thermal foggers have been widely used for mosquito control (Brown 1968, Buzicky 1968, Berry 1971, Taylor and Schoof 1971, Rathburn 1972, Mount et al. 1975, Linley and Jordan 1992, Rose 2001). In vector control, Seleena et al. (2001) studied thermal application of *Bacillus thuringiensis* var. *israelensis* for dengue vector control using a thermal fogger. Matthews (1996), using thermal foggers for dengue vector control, pointed out that the evaluation of thermal fogging equipment is similar to aerosol generators (cold foggers), but droplet sizing is difficult due to obscuration of the laser beam unless the fog is sampled and diluted. Other applications of thermal foggers are for control of sylvatic vectors of yellow fever (Bang 1980), control of *Aedes aegypti* Linnaeus-borne epidemics (Chow 1977), control of *Ae. aegypti* (Wirat 1982), control of St. Louis encephalitis, and control of *Stegomyia fasciata* Linnaeus (Brown 1972).

Brown et al. (1993) studied the temperature and flow rate effects on mass median diameter of thermally generated malathion and naled fogs. Rathburn et al. (1965) conducted comparative tests of fog oils and diesel oil as thermal aerosols for control of mosquitoes. Ledson and Matthews (1992) measured droplet spectra of 3 thermal fogging machines when applying the sprout suppressant chlorpropham (Unicrop CIPC) to treat potatoes in large stores using a laser light diffraction

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Fig. 1. Testing of thermal fogging atomizer equipment.

particle size analyzer. Lafferty (1962) completed a full season of work with 2 gas-powered thermal fogging machines for mosquito control.

The labels on the pesticides included in this testing provide users with droplet size requirements that generally fall between 8 and 30 μm $D_{V0.5}$ with at least 90% of the volume contained in droplets $<50 \mu\text{m}$. The labels require that users adjust sprayers to produce droplets that meet these requirements based on droplet sizing measurements made with laser-based measurement systems. Generating droplet size data and guidance to meet these label requirements was a primary objective for conducting the testing that is reported in this manuscript. Another objective of this study was to use a laser diffraction droplet analysis system to obtain baseline droplet and spray cloud formation information on available thermal fogging equipment that are incorporated or could be potential candidates for incorporation into Department of Defense pest management programs, thereby providing program managers with the information that will allow them to select the sprayer for their particular needs. Additionally, 2 sprayers that produce cold fog and ULV sprays were evaluated.

MATERIALS AND METHODS

A total of 56 replicated spray tests, comprising 11 sprayers and 4 pesticides used in vector control

applications, were completed for this study. The sprayers were selected from equipment that is commonly used for vector and flying insect control applications. The specific testing protocol, spray formulations, equipment tested, and physical property measurement procedures are discussed in the following sections.

Droplet sizing

For each combination of sprayer and pesticide formulation, 3 independent replications were conducted. A replication comprised operating the sprayer for a short period (10–50 sec depending on the sprayer) to allow the sprayer to reach operating temperature and to produce a thermally generated fogging spray. The Sympatec laser system was positioned 1–3 m from the outlet of the sprayer (Fig. 1). After the sprayer reached operating temperature, the spray cloud was directed toward the laser system for 5–20 sec during which time droplet size measurements of the spray cloud were made. The time that the spray cloud was directed through the optical path of the laser varied between sprayers depending on the density of the spray. Very dense fogs caused laser obscuration, which was immediately noticed by the laser operator. To overcome this, these dense fogs were directed at the laser system for short time periods to help dilute the spray fog. Appropriate personal protective equipment, such

as respirators, gloves, goggles, and Tyvek suits (DuPont, Wilmington, DE), were worn during all tests containing active ingredients.

Droplet sizing system: A Sympatec Helos laser diffraction droplet sizing system (Sympatec Inc., Clausthal, Germany) was utilized in this study. The Helos system uses a 623-nm He-Ne laser and was fitted with an R5 lens, which made the dynamic size range from 0.5 μm to 875 μm in 32 sizing bins. A specially constructed frame and forklift was used to hold the unit while the spray plume was directed through the laser.

The spray droplet size data were determined and reported as a mean and standard deviation corresponding to the data measured during the 3 replications for each combination of sprayer and pesticide. Means and standard deviations of the volume median diameter (VMD or $D_{V0.5}$), $D_{V0.1}$, and $D_{V0.9}$ were determined. The $D_{V0.5}$ is the droplet diameter (μm) at which 50% of the spray volume is contained in droplets smaller than this value. Similarly, the $D_{V0.1}$ and $D_{V0.9}$ values are the diameters at which 10% and 90%, respectively, of the spray volume is contained in droplets of this size or less. The percentage of spray volume contained in droplets $<20 \mu\text{m}$ (%Vol $<20 \mu\text{m}$) was calculated for all tests, as it allows the equipment user to determine the portion of the applied material that will most likely stay aloft after an application and potentially impinge on flying insects.

Teflon-coated glass slides: To capture the spray droplets, 25-mm-wide Teflon-coated slides were hand-slung through the spray clouds as described by Rathburn (1970). After passing through the spray cloud, the slides were removed and placed in sealed slide racks to prevent any additional exposure. Two hundred randomly selected droplets were measured under a calibrated microscope. The $D_{V0.5}$ for each slide was computed by inputting the collected droplet data into the Droplet Analysis Program available from Adapco Inc. (Sanford, FL). Because there were several different compounds used in this study, different spread factors were used by the Adapco Droplet Analysis Program to calculate droplet size. The spread factors used for Anvil[®] 10+10, Aqualuer[®] 20-20, Aqua-Reslin[®], Fyfanon[®], and Kontrol[®] 30-30 materials were 0.63, 0.61, 0.69, 0.65, and 0.63, respectively. The Droplet Analysis Program calculation of VMD is based on diameter values rather than volume associated with each droplet diameter. This correction is based on work reported by Yeoman (1949) and is done to remove the bias toward the collection of larger droplets by a moving slide.

Spray formulations

Five pesticides were evaluated. Active ingredient (AI) mix ratios are shown in Tables 1-3.

These data are included with the results to directly tag the measured droplet size data to the operating characteristics. Note that though the AI mix ratios vary from sprayer to sprayer, they were mixed such that given sprayer flow rate and based on a moving speed of 8 km/h (5 mph) (even though the sprayer was not moving), the AI application rate for a given insecticide remained constant across all sprayers. The following are the names, chemical makeup, manufacturer, and label information detailing specific droplet size requirements:

Anvil 10+10 ULV: 3-Phenoxybenzyl-(1RS, 3RS, 1RS, 3SR)-2,2-dimethyl-3-(2-methylprop-1-enyl) cyclopropanecarboxylate and piperonyl butoxide (Clark Mosquito Control Products Inc., Roselle, IL). "Spray equipment must be adjusted so that the ... VMD is 8 to 30 microns and that 90% of the spray is contained in droplets smaller than 50 microns." Product "... may be applied with suitable thermal fogging equipment."

Aqualuer 20-20: Permethrin and piperonyl butoxide (Value Garden Supply, St. Joseph, MO). "Spray equipment must be adjusted so the (VMD) ... is less than 30 microns and that 90% of the spray is contained in droplets smaller than 48 microns."

Aqua-Reslin: Permethrin and piperonyl butoxide (Bayer Environmental Science, Montvale, NJ). "Spray equipment should be adjusted so that the VMD is less than 30 μm and that 90% of the spray is contained in droplets smaller than 50 μm ."

Fyfanon ULV: Malathion (Cheminova A/S, Lemvig, Denmark). "Spray equipment must be adjusted so that the (VMD) ... is less than 17 μm and that 90% of the spray is contained in droplets smaller than 32 μm ."

Kontrol 30-30: Permethrin and piperonyl butoxide (Univar USA, Inc., Austin, TX). "Spray equipment (Thermal and Non-thermal) must be adjusted so that the (VMD) ... is less than 30 μm and that 90% of the spray is contained in droplets smaller than 48 μm ."

These products were diluted in water or diesel (automotive grade) at various ratios as specified in the Results section. Kontrol 30-30 was also evaluated undiluted in some of the trials.

Equipment

Eleven thermal foggers, as described below, were evaluated in this study. Note that the term "truck-mounted" is used to describe sprayers that must be moved via truck or 4-wheeler, while "backpack" describes sprayers that could be carried by one person.

London FogTM Eliminator (London Fog, Long Lake, MN): Study notation: LF Eliminator. Description—Handheld—The Eliminator utilizes the heat produced from a Tecumseh 2-cycle

Table 1. Spray droplet spectra data from the laser diffraction system and Teflon-coated slides for London FogTM (LF) and Curtis Dyna-Fog[®] (CDF) thermal fogging sprayers with pesticides diluted in diesel (pest:diesel), with maximum temperature measured at the spray nozzle.

Sprayer	Flow rate (oz/min) ¹	Pesticide	Dilution (pest:diesel)	Laser diffraction data ²				Slide data		Max. temperature (°C) (°F) ³
				D _{v0.1} (μm ± SD)	D _{v0.5} (μm ± SD)	D _{v0.9} (μm ± SD)	%Vol < 20 μm	D _{v0.5} (μm)	%Vol < 20 μm	
LF Eliminator	(10.7)	Fyfanon	1:18.3	1.2 ± 0.2	4.2 ± 0.9	9.7 ± 0.9	99.5	12.9	74.3	187 (368)
		Anvil 10+10	1:7.7	1.3 ± 0.1	4.4 ± 0.7	9.9 ± 1.8	99.9	24.7	36.5	138 (280)
LF F500	(53.3)	Kontrol 30-30	1:39	1.2 ± 0.0	3.8 ± 0.0	8.6 ± 0.1	100.0	29.5	20.0	196 (384)
		Fyfanon	1:91.5	1.6 ± 0.4	5.4 ± 1.4	11.4 ± 2.2	99.8	5.7	100.0	171 (340)
		Anvil 10+10	1:38.5	1.2 ± 0.1	4.0 ± 0.5	8.7 ± 1.4	100.0	6.2	100.0	209 (409)
		Kontrol 30-30	1:195	19.6 ± 4.6	45.4 ± 4.7	68.6 ± 5.0	10.8	9.9	91.8	210 (410)
CDF Golden Eagle	(10.7)	Fyfanon	1:18.3	1.2 ± 0.0	4.0 ± 0.2	9.5 ± 0.6	100.0	N/A ⁴	N/A	193 (380)
		Anvil 10+10	1:7.7	1.3 ± 0.1	4.5 ± 0.4	9.9 ± 0.9	100.0	7.1	91.4	226 (440)
CDF Silver Cloud	(22.0)	Kontrol 30-30	1:39	1.5 ± 0.1	5.6 ± 0.4	14.0 ± 0.8	97.7	16.1	56.7	224 (436)
		Kontrol 30-30	Undiluted	0.9 ± 0.0	2.6 ± 0.1	4.2 ± 0.1	99.9	N/A	N/A	242 (468)
		Kontrol 30-30	Undiluted	1.6 ± 0.3	5.6 ± 1.4	11.3 ± 1.7	99.9	N/A	N/A	238 (460)
		Fyfanon	1:91.5	1.0 ± 0.1	3.1 ± 0.4	6.0 ± 1.5	100.0	14.2	63.0	299 (570)
CDF 1200	(53.3)	Anvil 10+10	1:38.5	1.1 ± 0.0	3.6 ± 0.1	7.5 ± 0.4	100.0	11.3	93.0	264 (508)
		Kontrol 30-30	1:195	19.2 ± 0.6	75.5 ± 2.3	137.1 ± 1.9	12.0	N/A	N/A	211 (412)
		Kontrol 30-30	1:39	4.7 ± 2.9	17.9 ± 5.0	66.9 ± 3.5	52.9	N/A	N/A	N/A
		Fyfanon	1:91.5	1.2 ± 0.2	4.0 ± 0.9	9.9 ± 2.1	99.8	6.2	100.0	207 (405)
CDF Trailblazer	(10.7)	Kontrol 30-30	1:195	1.3 ± 0.2	4.5 ± 1.2	13.4 ± 2.4	97.8	42.2	20.8	338 (640)
		Fyfanon	1:18.3	1.4 ± 0.1	5.1 ± 0.6	12.8 ± 1.0	98.9	7.8	81.5	302 (576)
		Anvil 10+10	1:7.7	0.9 ± 0.0	2.6 ± 0.1	4.3 ± 0.3	99.8	8.8	88.1	254 (489)
		Kontrol 30-30	1:39	2.6 ± 0.8	8.6 ± 1.8	16.4 ± 1.9	96.3	15.0	71.9	286 (546)
		Aqualuer	1:26.8	1.1 ± 0.1	3.6 ± 0.6	8.0 ± 1.9	99.9	14.2	74.5	317 (602)

¹ Flow rate represented the application rate if the sprayer was moving at 8 km/h (5 mph); however, sprayer was not moving during these studies.

² D_{v0.1}, D_{v0.5}, D_{v0.9}, droplet diameter (μm) at which 10%, 50%, and 90%, respectively, of the spray volume is contained in droplets smaller than this value; %Vol < 20 μm, percentage of spray volume contained in droplets < 20 μm.

³ Maximum temperature measured at the release point (e.g., nozzle or outlet) of the spray.

⁴ N/A, data were not collected.

Table 2. Spray droplet spectra data from the laser diffraction system and Teflon-coated slides for Tifa® and Swinglee (ST) thermal fogging sprayers with pesticides diluted in diesel (pest:diesel), with maximum temperature measured at the spray nozzle.

Sprayer	Flow rate (oz/min) ¹	Pesticide	Dilution (pest:diesel)	Laser diffraction data ²				Slide data		Max. temperature (°C) (°F) ³
				D _{v0.1} (μm ± SD)	D _{v0.5} (μm ± SD)	D _{v0.9} (μm ± SD)	%Vol < 20 μm	D _{v0.5} (μm)	%Vol < 20 μm	
Tifa 1504	(53.3)	Fyfanon	1:91.5	14.9 ± 3.9	33.3 ± 5.4	60.7 ± 6.2	24.3	32.2	29.3	225 (437)
		Anvil 10+10	1:38.5	8.3 ± 2.4	15.3 ± 1.9	24.4 ± 2.8	74.5	12.8	83.0	210 (409)
Tifa 100E	(53.3)	Fyfanon	1:91.5	2.6 ± 0.9	27.0 ± 22.1	93.6 ± 12.9	45.0	29.0	31.5	323 (615)
		Anvil 10+10	1:38.5	1.5 ± 0.1	5.9 ± 0.5	49.2 ± 3.4	78.0	30.3	28.9	342 (648)
ST SN50	(10.7)	Kontrol 30-30	1:195	4.6 ± 4.0	20.9 ± 17.1	74.8 ± 13.3	52.6	30.8	31.7	342 (648)
		Fyfanon	1:18.3	1.1 ± 0.1	3.4 ± 0.4	7.0 ± 1.3	100.0	15.0	64.8	173 (343)
ST SN101	(53.3)	Anvil 10+10	1:7.7	1.3 ± 0.1	4.5 ± 0.6	11.1 ± 1.0	99.7	7.7	98.7	297 (556)
		Kontrol 30-30	1:39	1.2 ± 0.1	3.8 ± 0.2	8.4 ± 1.1	99.9	16.4	68.3	N/A ⁴
ST SN101	(53.3)	Aqualer	1:26.8	1.4 ± 0.2	4.1 ± 0.2	25.6 ± 10.5	87.9	14.5	78.5	323 (613)
		Fyfanon	1:91.5	1.4 ± 0.2	4.8 ± 1.1	11.3 ± 1.3	99.5	14.4	60.9	170 (338)
ST SN101	(53.3)	Anvil 10+10	1:38.5	1.5 ± 0.5	5.2 ± 1.7	11.3 ± 2.1	99.7	11.3	80.8	277 (530)
		Kontrol 30-30	1:195	5.7 ± 4.8	13.1 ± 7.2	59.9 ± 8.0	60.3	24.6	27.3	253 (487)

¹ Flow rate represented the application rate if the sprayer was moving at 8 km/h (5 mph); however, sprayer was not moving during these studies.

² D_{v0.1}, D_{v0.5}, D_{v0.9}, droplet diameter (μm) at which 10%, 50%, and 90%, respectively, of the spray volume is contained in droplets smaller than this value; %Vol < 20 μm, percentage of spray volume contained in droplets < 20 μm.

³ Maximum temperature measured at the release point (e.g., nozzle or outlet) of the spray.

⁴ N/A, data were not collected.

Table 3. Spray droplet spectra data from the laser diffraction system and Teflon-coated slides for Curtis Dyna-Fog® (CDF), Tifa®, and Swinglec (ST) thermal fogging sprayers with pesticides diluted in water (pest:water), with maximum temperature measured at the spray nozzle.

Sprayer	Flow rate (oz/min) ¹	Pesticide	Dilution (pest:water)	Laser diffraction data				Slide data		Max. temperature (°C) (°F) ³
				D _{v0.1} (μm ± SD)	D _{v0.5} (μm ± SD)	D _{v0.9} (μm ± SD)	%Vol < 20 μm	D _{v0.5} (μm)	%Vol < 20 μm	
CDF Trailblazer	(10.7)	Aqualuer	1:26.8	13.0 ± 0.5	31.9 ± 2.6	85.6 ± 19.4	25.9	7.0	96.2	212 (414)
		Aqua-Reslin	1:25.5	15.7 ± 0.8	40.7 ± 1.9	97.8 ± 5.2	17.0	40.2	6.4	167 (332)
CDF Mister	(10.7)	Aqualuer	1:26.8	13.9 ± 0.4	36.9 ± 0.3	87.4 ± 1.9	21.0	8.9	95.3	303 (579)
		Aqua-Reslin	1:25.5	11.8 ± 0.7	27.9 ± 0.2	57.6 ± 3.3	30.7	43.0	5.9	337 (617)
Tifa 100E	(53.3)	Aqualuer	1:134	15.7 ± 0.4	43.5 ± 0.8	86.4 ± 0.1	15.3	7.0	96.5	320 (608)
		Aqua-Reslin	1:127.5	21.8 ± 1.4	59.9 ± 2.5	124.1 ± 3.4	8.5	N/A ⁴	N/A	321 (610)
ST SN50	(10.7)	Aqualuer	1:26.8	16.1 ± 0.6	32.1 ± 0.7	70.1 ± 5.7	19.5	7.0	95.7	334 (633)
		Aqua-Reslin	1:25.5	12.4 ± 0.5	29.7 ± 0.8	54.8 ± 2.3	25.2	27.9	15.2	330 (626)
ST SN101	(53.3)	Aqualuer	1:134	18.1 ± 0.6	49.0 ± 4.5	94.2 ± 9.7	12.5	5.6	93.2	N/A
		Aqua-Reslin	1:127.5	16.0 ± 0.7	47.9 ± 2.9	92.5 ± 4.6	15.2	11.9	66.9	325 (617)
		Aqualuer	1:134	17.8 ± 1.7	35.5 ± 2.8	77.2 ± 8.9	15.2	N/A	N/A	275 (528)
		Aqua-Reslin	1:127.5	16.2 ± 0.4	35.5 ± 1.4	63.6 ± 1.6	17.2	30.9	3.8	N/A

¹ Flow rate represented the application rate if the sprayer was moving at 8 km/h (5 mph); however, sprayer was not moving during these studies.

² D_{v0.1}, D_{v0.5}, D_{v0.9}, droplet diameter (μm) at which 10%, 50%, and 90%, respectively, of the spray volume is contained in droplets smaller than this value; %Vol < 20 μm, percentage of spray volume contained in droplets < 20 μm.

³ Maximum temperature measured at the release point (e.g., nozzle or outlet) of the spray.

⁴ N/A, data were not collected.

gasoline engine, with a manual recoil start, to create a dense dry fog at a flow rate of 6 gal (23 liters)/h. It has a net weight of 24 lb (11 kg) with dimensions of 25 in. long (L) \times 11 in. wide (W) \times 21 in. high (H) (64 cm L \times 27 cm W \times 52 cm H). It is designed to be used with petroleum-based insecticide formulations or odor control chemicals.

London Fog F 500-E (London Fog): Study notation: LF F500. Description—Truck-mounted—The F 500E utilizes a 2-stage turbo-rotor or mechanical viscous friction-induced heating with hot air blasts to create a dry thermal fog. The turbo-rotor is directly mounted to the crankshaft of a 16-hp 4-cycle gasoline engine with an electric start. This thermal fogger has a net weight of 220 lb (100 kg) and a maximum flow rate of 35 gal (133 liters)/h. The dimensions of this piece of equipment are 30 in. L \times 33 in. W \times 24 in. H (76 cm L \times 84 cm W \times 61 cm H). This equipment is designed to be used with petroleum-based insecticide formulations.

Curtis Dyna-Fog® Golden Eagle™, Model 2610, Series 3 (Curtis Dyna-Fog Ltd., Westfield, IN): Study notation: CDF Golden Eagle. Description—Handheld—The Golden Eagle utilizes a gasoline-powered 30-hp pulse jet engine or a resonant pulse to produce a thermal fog. This thermal fogger has a net weight of 19 lb (9 kg) and a maximum flow rate of 9 gal (34 liters). The dimensions of this piece of equipment are 52 in. L \times 10 in. W \times 15 in. H (132 cm L \times 24 cm W \times 37 cm H). This equipment is designed to disperse petroleum-based insecticide formulations, fungicides, germicides, disinfectants, and odor control chemicals.

Curtis Dyna-Fog Silver Cloud™, Model 2560, Series 2 (Curtis Dyna-Fog Ltd.): Study notation: CDF Silver Cloud. Description—Truck-mounted—The Silver Cloud utilizes gasoline-powered twin pulse jet engines or a resonant pulse to produce a thermal fog. The combined horsepower of the engines is 88. This thermal fogger has a net weight of 106 lb (48 kg) and a flow rate of 40 gal (152 liters)/h. The dimensions of this piece of equipment are 68 in. L \times 24 in. W \times 22 in. H (173 cm L \times 61 cm W \times 56 cm H). This equipment is designed to disperse petroleum-based insecticide formulations.

Curtis Dyna-Fog Model 1200™, diesel: PIN-49000-22 (Curtis Dyna-Fog Ltd.): Study notation: CDF 1200. Description—Truck-mounted—The Model 1200 utilizes an 11-hp Yanmar diesel engine to drive the blower of the fuel oil burner (combustion chamber), the formulation pump, and the 120-V alternating current, 60-Hz 1,000-W generator. The oil burner pump is driven from the blower drive shaft. The blower and combustion chamber create heated high-velocity gases that vaporize the formulation, creating the thermal fog. The Model 1200 can be adjusted to produce a wet or dry fog. This thermal fogger has a net

weight of 502 lb (228 kg) and a maximum flow rate of 120 gal (454 liters)/h. This fogger has the capacity to fog 12 acres (49,000 m²)/min. The dimensions of this piece of equipment are 79 in. L \times 35 in. W \times 32 in. H (199 cm L \times 89 cm W \times 81 cm H). This equipment is designed to disperse petroleum-based insecticide and fungicide formulations.

Curtis Dyna-Fog Trailblazer™ (Curtis Dyna-Fog Ltd.): Study notation: CDF Trailblazer. Description—Handheld—The Trailblazer utilizes a 24-hp gasoline resonant-pulse jet engine to create the thermal fog. This thermal fogger has a net weight of 25 lb (11 kg) and a maximum flow rate of 5 gal (11 liters)/h. The dimensions of this piece of equipment are 29 in. L \times 10 in. W \times 18 in. H (74 cm L \times 25 cm W \times 46 cm H). This equipment is designed to disperse insecticides, fungicides, germicides, disinfectants, and odor control chemicals of both petroleum- and water-based formulations.

Curtis Dyna-Fog Mister III (Curtis Dyna-Fog Ltd.): Study notation: CDF Mister. Description—Handheld—The Mister III utilizes a 44-hp gasoline resonant-pulse jet engine to create the thermal fog. This thermal fogger has a net weight of 39 lb (18 kg) and a maximum flow rate of 12 gal (45 liters)/h. The dimensions of this piece of equipment are 61 in. L \times 15 in. W \times 17 in. H (160 cm L \times 25 cm W \times 46 cm H). This equipment is designed to disperse insecticides, fungicides, germicides, and disinfectants of water-based formulations.

Tifa® Model 1504 (Tifa International, LLC, Millington, NJ): Study notation: Tifa 1504. Description—Truck-mounted—The Model 1504 utilizes an 8-hp gasoline 4-cycle, single-cylinder internal combustion engine to create the spray application. This thermal fogger has a net weight of 340 lb (155 kg) and a maximum flow rate of 32 gal (121 liters)/h. The dimensions of this piece of equipment are 40 in. L \times 26 in. W \times 36 in. H (102 cm L \times 66 cm W \times 91 cm H). This piece of equipment is designed to disperse insecticides of both petroleum- and water-based formulations. The Model 1504 has the capability of producing thermal fog, as well as ULV cold aerosol and mist applications.

Tifa Model 100E (Tifa International): Study notation: Tifa 100E. Description—Truck-mounted—The Model 100E utilizes an 11-hp gasoline 4-cycle, single-cylinder internal combustion engine to create the spray application. This thermal fogger has a net weight of 576 lb (262 kg) and a maximum flow rate of 55 gal (209 liters)/h. The dimensions of this piece of equipment are 35 in. L \times 33 in. W \times 39 in. H (89 cm L \times 84 cm W \times 99 cm H). This piece of equipment is designed to disperse insecticides of both petroleum- and water-based formulations. The Model 100E has the capability of producing thermal fog, as well as ULV cold aerosol and mist applications.

Swingtec Swingfog® SN 50 (Swingtec GmbH, Isny, Germany): Study notation: ST SN50. Description—Handheld—The SN 50 utilizes a gasoline-powered 25-hp pulse jet engine or a resonant pulse at 80–110 pulses/sec to produce a thermal fog. This thermal fogger has a net weight of 19 lb (9 kg) and a maximum flow rate of 11 gal (42 liters)/h. The dimensions of this piece of equipment are 52 in. L × 11 in. W × 13 in. H (133 cm L × 29 cm W × 33 cm H). This piece of equipment is designed to disperse petroleum- and water-based chemicals when the appropriate fogging attachments are used. The SN 50 is designed to disperse insecticide, fungicide, and disinfectant formulations.

Swingtec Swingfog SN 101 M (Swingtec GmbH): Study notation: ST SN101. Description—Truck-mounted—The SN 101 M utilizes a gasoline-powered 57-hp pulse jet engine or a resonant pulse at 80–110 pulses/sec to produce a thermal fog. This thermal fogger has a net weight of 88 lb (40 kg) and a maximum flow rate of 32 gal (120 liters)/h. The dimensions of this piece of equipment are 70 in. L × 25 in. W × 13 in. H (177 cm L × 63 cm W × 22 cm H). This piece of equipment is designed to disperse petroleum- and water-based chemicals when the appropriate fogging attachments are used. The SN 101 M is designed to disperse insecticide, fungicide, and disinfectant formulations.

Temperature measurements

Temperature measurements were made with infrared, noncontact, handheld thermometer (Model 42545; Extech, Waltham, MA) with a measurement range of –50 to 1,000°C (–58 to 1,832°F). For each of the sprayers, temperature measurements were made at the nozzle tip where the spray came out. The maximum temperature recorded for each of the sprayers is presented in Tables 1–3.

Statistical analyses

The objective of this study was not to rank or statistically separate the sprayers; therefore, no statistical analyses of the data were performed. The means and the standard deviations of the droplet size parameters are presented.

RESULTS

Insecticide-specific atomization results

Results with respect to each tested insecticide are discussed below. Droplet size data and observations, as to whether label-specific droplet size requirements were met, were made for the different sprayers, dilutions, and rates tested.

Anvil 10+10: The thermal foggers tested using Anvil 10+10, at any dilution, resulted in VMDs

ranging from 2.6 to 15.3 μm (Tables 1 and 2). The $D_{V0.9}$ values ranged from 4.3 to 49.2 μm (Tables 1 and 2). Given that the label states Anvil may be applied with “suitable” thermal foggers, all equipment tested can be used. The Tifa 100E produced a $D_{V0.9}$ of 49.2 (Table 2), which is borderline based on the label requirements for ground application equipment.

Aqualuer 20-20: Though typically diluted with water, 2 trials were run with Aqualuer diluted with diesel (1:26.8) and applied with thermal foggers: the CDF Trailblazer and the ST SN50. The VMD and $D_{V0.9}$ values were 3.6 and 8.0 μm , respectively, for the CDF Trailblazer (Table 1), and 4.1 and 25.6 μm , respectively, for the ST SN50 (Table 2). Both thermal foggers were acceptable with respect to droplet size when applying the diesel dilutions. For thermal fog applications with water dilutions of Aqualuer, VMDs ranged from 31.9 to 49 μm and $D_{V0.9}$ s ranged from 70.1 to 94.2 μm (Table 3). None of these applications meet label requirements.

Aqua-Reslin: Thermal fogging trials using water-diluted mixtures resulted in VMDs ranging from 27.9 to 59.9 μm and $D_{V0.9}$ s ranging from 57.6 to 124.1 μm (Table 3). The CDF Mister and the ST SN50 both meet the label requirement for VMD, but none of the sprayers tested meet the requirement of a maximum $D_{V0.9}$ of 50 μm .

Fyfanon: Thermal fogging trials using Fyfanon diluted with diesel resulted in VMDs ranging from 3.1 to 33.0 μm and $D_{V0.9}$ s ranging from 7.0 to 93.6 μm (Tables 1 and 2). All sprayers except the Tifa 1504 and the Tifa 100E meet the label requirements for VMD and $D_{V0.9}$.

Kontrol 30-30: Thermal fogging applications of Kontrol resulted in VMDs ranging from 2.6 to 75.5 μm and $D_{V0.9}$ s ranging from 4.2 to 137.1 μm (Tables 1 and 2). The LF Eliminator, the CDF Golden Eagle (both flow rates and dilutions), the CDF 1200, the CDF Trailblazer, and the ST SN50 meet all label requirements. The CDF Silver Cloud (1:39 dilution), the Tifa 100E, and the ST SN101 meet the VMD required size limit of 30 μm but do not meet the maximum $D_{V0.9}$ size of 48 μm . The LF F500 and CDF Silver Cloud (1:195 dilution) do not meet either of the labeled droplet size requirements.

Sprayer temperature results

The temperatures measured for the sprayers ranged from 138 to 323°C (280–648°F) for the sprayers tested (Tables 1–3). The range of temperatures highlights the different atomization methods used by the different machines.

Comparison of droplet measurement systems

The droplet sizes measured by the swinging slide method did not consistently match the

droplet sizes measured by the laser diffraction instrument (Tables 1–3). Due to time and labor constraints during the testing, only 1 slide was used for each trial whereas 3 replications were completed with the laser diffraction instrument. The droplets produced by the thermal fogging equipment were very small, which would lead to a low collection efficiency (May and Clifford 1967) on the glass slides and could have preferentially sampled the larger droplets ($>20\ \mu\text{m}$) in the spray cloud.

DISCUSSION

The objectives of this work were to present not only information on spray-system droplet size generated by different sprayers, but to compare methodologies by which other similar systems can be evaluated and give applicators sprayer-system performance data. While many researchers (Buzicky 1968, Ledson and Matthews 1992, Brown et al. 1993) have reported droplet size for different equipment and formulations, the work presented in this manuscript is unique in the number of sprayers tested at one time using the same droplet measurement technique, which was a laser diffraction instrument. There was a wide range in the droplet size spectra produced by the different sprayers tested. This variety in equipment performance is similar to that reported for handheld vector control equipment (Hoffmann et al. 2007b) and truck-mounted equipment (Hoffmann et al. 2007a).

In these studies, the $D_{V0.5}$ measurements for the sprays diluted in diesel ranged from 2.6 to 75.5 μm depending on the sprayer and the %Vol $<20\ \mu\text{m}$ ranged between 12.0% and 100%. The $D_{V0.5}$ measurements for the sprays diluted in water ranged from 27.9 to 59.9 μm and the %Vol $<20\ \mu\text{m}$ ranged between 8.5% and 30.7%. The droplet sizes measured by the swinging slide method did not consistently match the droplet sizes measured by the laser diffraction instrument. Based on these trials, the use of the swinging slide method for sampling thermal fog sprays is not recommended without additional study examining the relationship between laser diffraction-based droplet size measurements and swinging slide measurements.

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